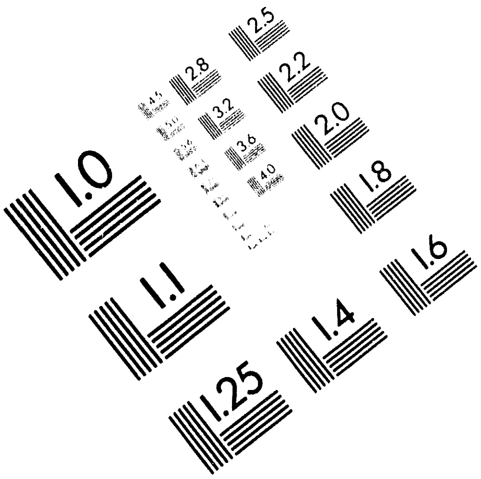

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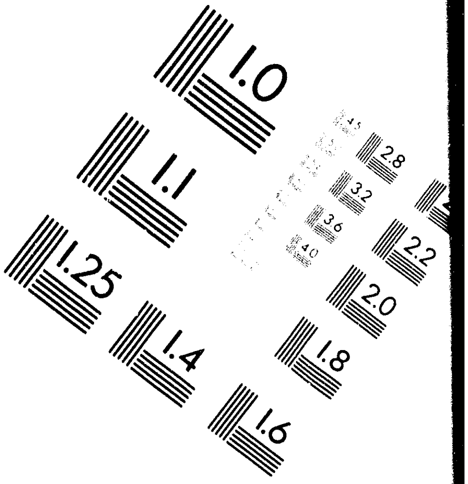

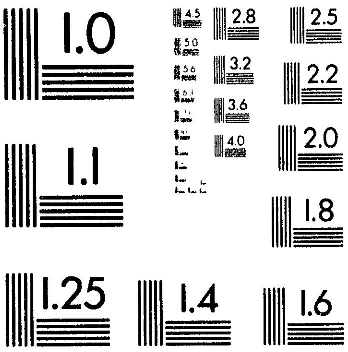

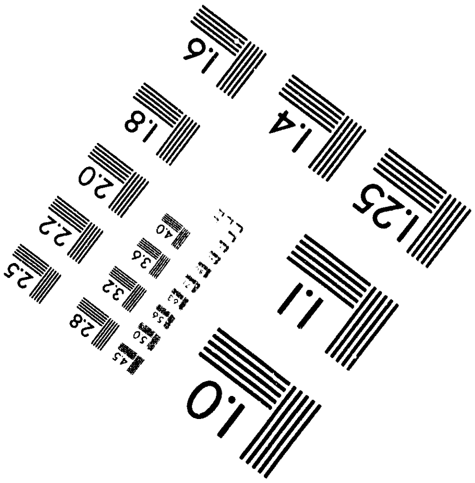

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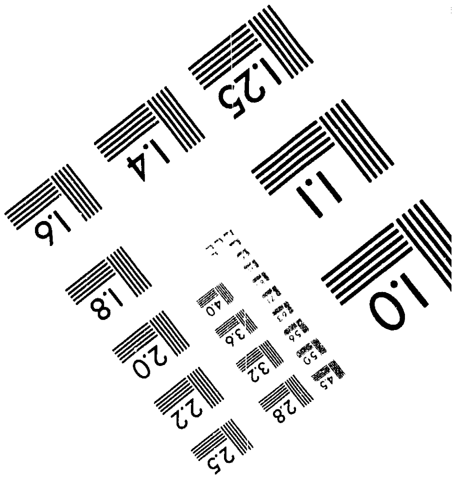

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An X-Ray Technique for Precision Laser Beam Synchronization

O. L. Landen, R. A. Lerche, R. G. Hay, B. A. Hammel,
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Lawrence Livermore National Laboratory

An X-Ray Technique for Precision Laser Beam Synchronization

O.L. Landen, R.A. Lerche, R.G. Hay, B.A. Hammel, D. Kalantar and
M.D. Cable

Lawrence Livermore National Laboratory, P.O. Box 5508,
Livermore, CA 94550

Abstract

A new x-ray technique for recording the relative arrival times of multiple laser beams at a common target with better than ± 10 ps accuracy has been implemented at the Nova laser facility. 100 ps, 3ω Nova beams are focussed to separate locations on a gold ribbon target viewed from the side. The measurement consists of using well characterized re-entrant x-ray streak cameras for 1-dimensional streaked imaging of the > 3 keV x-rays emanating from these isolated laser plasmas. After making the necessary corrections for the differential laser, x-ray and electron transit times involved, timing offsets as low as ± 7 ps are resolved, and on subsequent shots, corrected for, verified and independently checked. This level of synchronization proved critical in meeting the power balance requirements for indirectly-driven pulse-shaped Nova implosions.

Synchronizing the arrival times of multiple laser beams is crucial for two important classes of laser-plasma experiments. First, there are shots requiring accurate knowledge of a preimposed probe beam delay. Examples are x-ray backlit Rayleigh-Taylor[1] and Richtmyer-Meshkov[2] experiments. Second, there are shots requiring good power balance at a common target. Examples are direct[3] and indirect-drive[4] implosions. A specific example is shown in Figure 1 for a laser pulse shape denoted #25 used in high convergence indirect-drive implosions at Nova. The evolution in laser intensity and average fractional power imbalance are plotted for a random distribution of beam timing offsets with a standard deviation Δt = 25 ps. For a given timing offset Δt, the fractional power imbalance $\Delta P/P$ is proportional to the fractional rate of change of power $(1/P)(dP/dt)$. Up to 8% power imbalance is noted midway in the pulse when the power is changing rapidly, unacceptable by Precision Nova power balance standards even before other sources of power imbalance are considered.

On a shot-to-shot basis, the relative beam arrival times are commonly obtained from streaked records[5,6] of the laser pulses sampled before they arrive at the target chamber. However, any change in the propagation delay between the sample point and the target cannot be detected from this data and at least one absolute calibration at the target is still needed. At the Nova 10-beam facility, synchronization at chamber center was traditionally set and checked semiannually by using streaked UV imaging[7] of low temperature plasmas created by focussing 100 ps, few joule pulses on a foil. Multiple shots were needed as only subsets of beams were selected per shot. In addition, only the leading edge of the streaked images could be used as the fall-times were much longer than the laser pulse duration. The quoted synchronization accuracy was ± 30ps root-mean-square (RMS).

An alternative x-ray technique based on the UV streaked method has been implemented. The advantages include: all 10 beams are recorded on a single shot, the full laser energy is used, hence mimicking the laser power used on most experimental shots, two separate measurements with two diagnostic cameras can be obtained on each shot for better confidence, the x-ray streak durations match those of the laser pulses and synchronization accuracy can be as good as ± 7 ps RMS.

Targets consist of gold foils in a ribbon geometry, ≈ 12-mm-high by 50-µm-thick by 400-µm wide. The cameras view the ribbon targets edge-on. The two clusters of beams arrive orthogonal to the camera axes plane, are focussed on both sides of the ribbon target to a 300-µm-diameter spot and are spaced 800 µm apart along a vertical line in order of increasing beam number. This ensures no spatial overlap and minimizes the beam steering necessary to position the extremal beams (#1 and 10). The focal spot size has been chosen large enough to minimize hard x-ray fogging yet smaller than the target width to avoid edge irradiation. The target width has been minimized to simplify edge-on alignment given finite depth-of-focus optics, thereby reducing partial vignetting from target tilt leading to compromising effects such as delayed and shortened x-ray emission. For maximum accuracy, the shortest conventional Nova laser pulse length is chosen, 100 ps full width at half maximum (FWHM) Gaussian at 1.064 µm. These pulses are frequency tripled to yield 300 J in 80 - 90 ps FWHM.

The synchronization measurements are performed by 1-dimensional x-ray streaked imaging[8] using well-characterized re-entrant streak cameras[9]. The cameras are equipped with 20-µm-high, 1-mm-long vertically imaging slits set for 2x overall magnification. The streak cameras have 1.26x internal magnification, are operated with a horizontal sweep speed of 30 - 35 ps/mm and are equipped with vertical 250-µm-wide time-resolving slits yielding 10 ps resolution. A 3 - 4.7 keV photon energy band is selected by typically filtering with 1 mm of Be and 25 µm of Ti. The streaked and intensified outputs are recorded with T-3200 film.

The thresholds for detrimental x-ray streak camera saturation and space-charge induced temporal distortion have been extensively characterized on the bench using 50 ps, 213 nm laser pulses. Linearity is preserved up to a film exposure level of ≈ 20 ergs/cm^2 at the camera settings used for beam synchronization shots. The onsets of space-charge induced temporal broadening and temporal shifts which would compromise accurate synchronization measurements are shown in Figs. 2a and b. Figure 2 dictates that the maximum camera outputs for synchronization data never exceed 10 ergs/cm^2.

Data from two sequential synchronization shots are shown in Figure 3. For Figure 3b, separate backlighter paths on two of the beams (#3 and 8) have also been checked. Line-outs are taken along the streak direction, fitted with Gaussian profiles and the peak positions recorded. Since each laser plasma emanates from a different spot, several corrections for differential laser, x-ray and streak camera electron transit times must be incorporated. While the first two are easily calculable by geometry, the electron transit time spread had to be ascertained on a separate 100 ps shot with the imaging slit removed. Such a streak exhibiting characteristic temporal curvature is shown in Fig. 4 along with quadratic fits for the two cameras employed. The sum of these corrections rarely exceeds ± 10 ps.

In addition to constant geometric path corrections, there is uncertainty in the orientation of the time-resolving slit relative to the sweep direction (nominally orthogonal), resulting in a possible shear in the space versus time axis at the film plane. For a given uncertainty in relative orientation, the shear timing error is proportional to sweep speed (in ps/mm) and hence can be reduced by increasing sweep speed (fewer ps/mm). However, the uncertainty can also be alleviated by recognizing that the relative slit orientation is conveniently recorded simultaneously by the transmitted x-ray signal which images the slit and hence appears as a bright rectangle (see Fig. 4 for example). The residual uncertainty estimated at ± 0.5° translates to only a ± 5 ps maximum error between the relative timing of the two extremal images in Figure 3.

The corrected data for the pre-existing offsets are shown as open circles in Figure 5. The data is reproducible to 7 ps RMS and suggests a desynchronization of 20 ps RMS. After applying a first round of beam timing corrections using the Nova variable optical delay lines, a second set of x-ray synchronization measurements were performed for which a typical streak is shown in Figure 6. The analyzed data is shown as filled circles in Figure 5. Ignoring beams 9 and 10 offsets which were later corrected, the residual desynchronization has been reduced to 7 ps RMS. Moreover, averaged over all beams, the standard deviation between timing shifts based on x-ray streaks, optical streaks before the target chamber, and delay line travel is only 3.5 ps.

Recently, the target geometry has been improved to eliminate the possibility of vignetting due to target tilt. The new targets are wedge-shaped, incorporate a vertical fiducial wire at the narrow end for tilt alignment and have both streak cameras facing the narrow end. The combination of wedge angle (≈ 5°) and fiducial allows for a much wider target (≈ 3 mm), hence eliminating edge irradiation. Although not necessary for Precision Nova goals, ± 2 ps accuracy should be possible with the present technique by using 20 ps Nova pulses and a faster sweep speed (10 ps/mm).

In summary, a new single-shot technique for high-power laser pulse synchronization with an accuracy better than 10 ps has been implemented at Nova. The pre-existing Nova mistiming was measured at 20 ps RMS, marginally satisfactory for the Precision Nova power balance goals, but a major limitation on the best power balance achievable in the absence of mistiming (e.g. 6% (3%) in the foot (peak) of pulse shape #25)[10]. After applying timing corrections dictated by the x-ray measurements, the residual power imbalance due to the residual asynchronicity of 7 ps RMS was < 2.5% RMS for pulse shape #25, and hence not a limiting factor anymore. The x-ray synchronization technique presented here should be applicable to future ICF facilities incorporating many more beams by subselecting up to 30 beams per shot (15 per side) and using one fiducial beam for cross-calibration.

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Figure Captions

Figure 1 Nova pulse shape #25 power (solid curve) and fractional power imbalance (dashed curve) for assumed 25 ps RMS desynchronization.

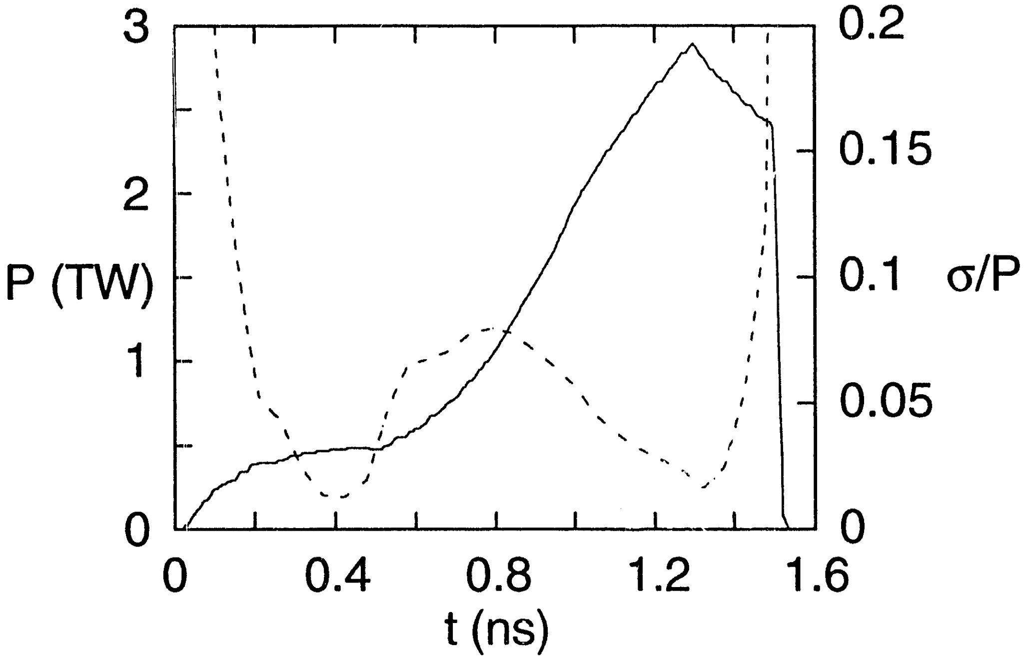
Figure 2 X-ray streak camera temporal distortion versus output signal. a). broadening and b) temporal shift.

Figure 3 X-ray streak records on two successive shots of pre-existing Nova desynchronization using 300 J, 3ω pulses. Resolution is 10 ps and photon energy is > 3 keV. BK refers to backlighter path.

Figure 4 a) Streak without imaging slit showing temporal curvature with image height. b) Temporal delay versus image height and quadratic fits for two streak cameras (SSC1, solid circles; SSC3, open circles).

Figure 5 Measured pre-existing beam offsets (open circles) and residual offsets after first round of corrections (closed circles) for all 10 Nova beams and three additional backlighter paths.

Figure 6 X-ray streak record after first round of corrections.



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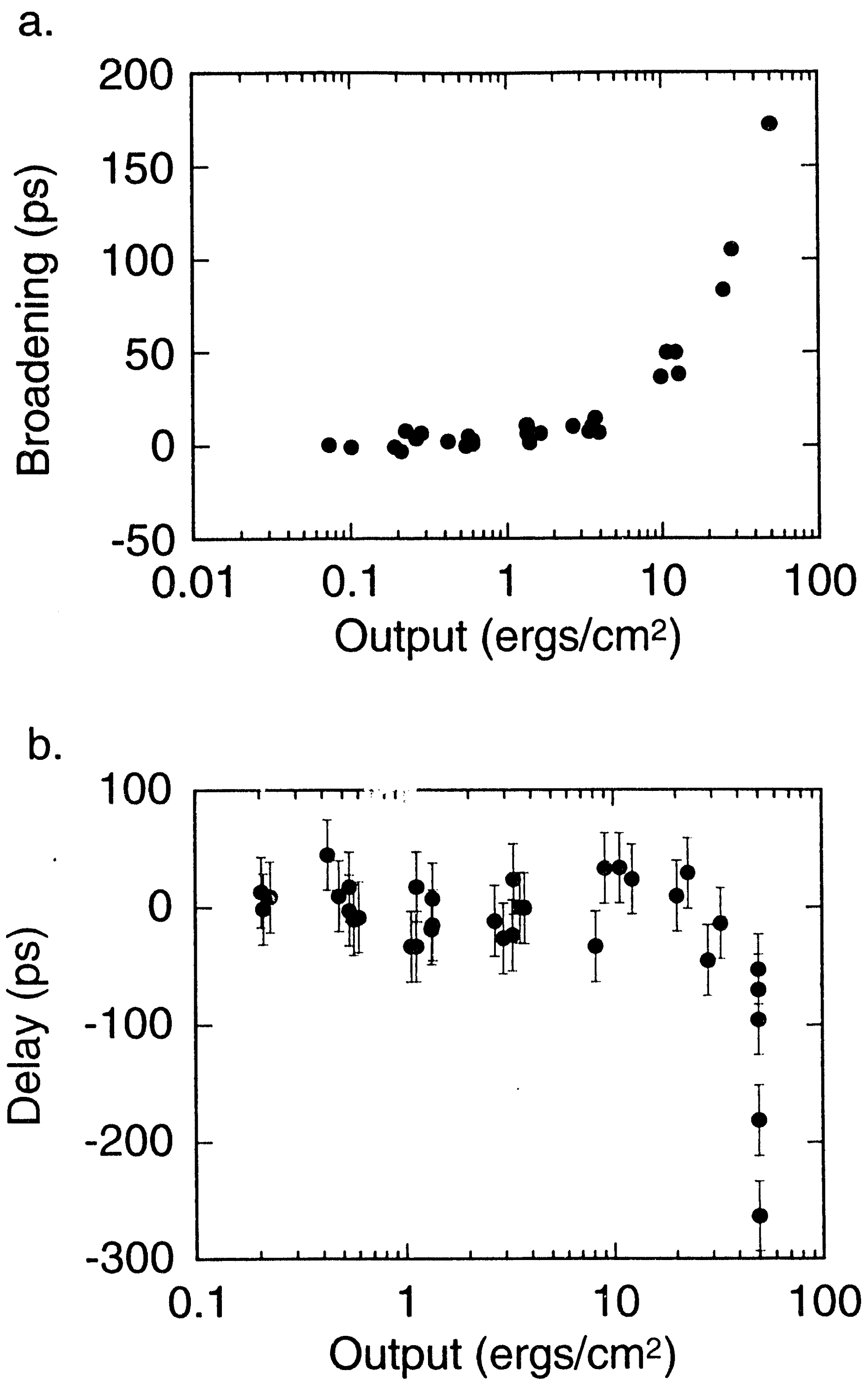
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150
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50
0
-50
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1
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b.
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0
-100
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-300
Delay (ps)
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10
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Output (ergs/cm2)

Figure 2

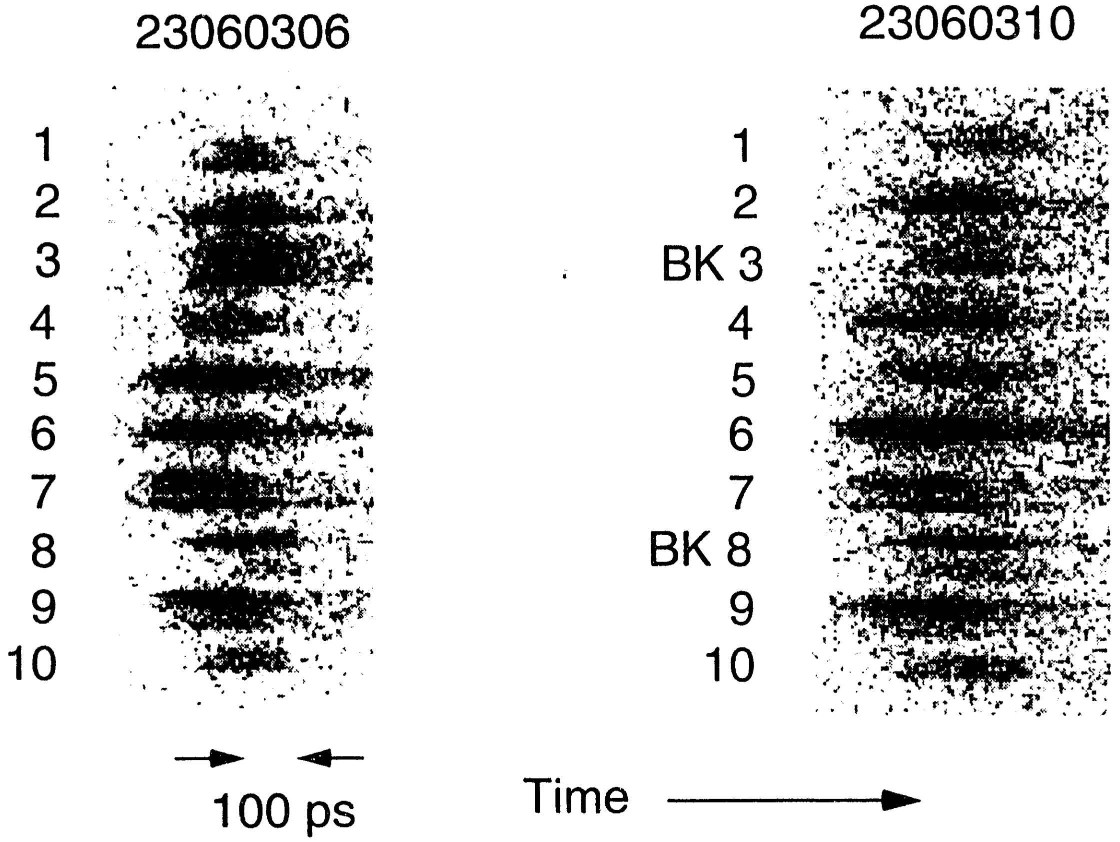
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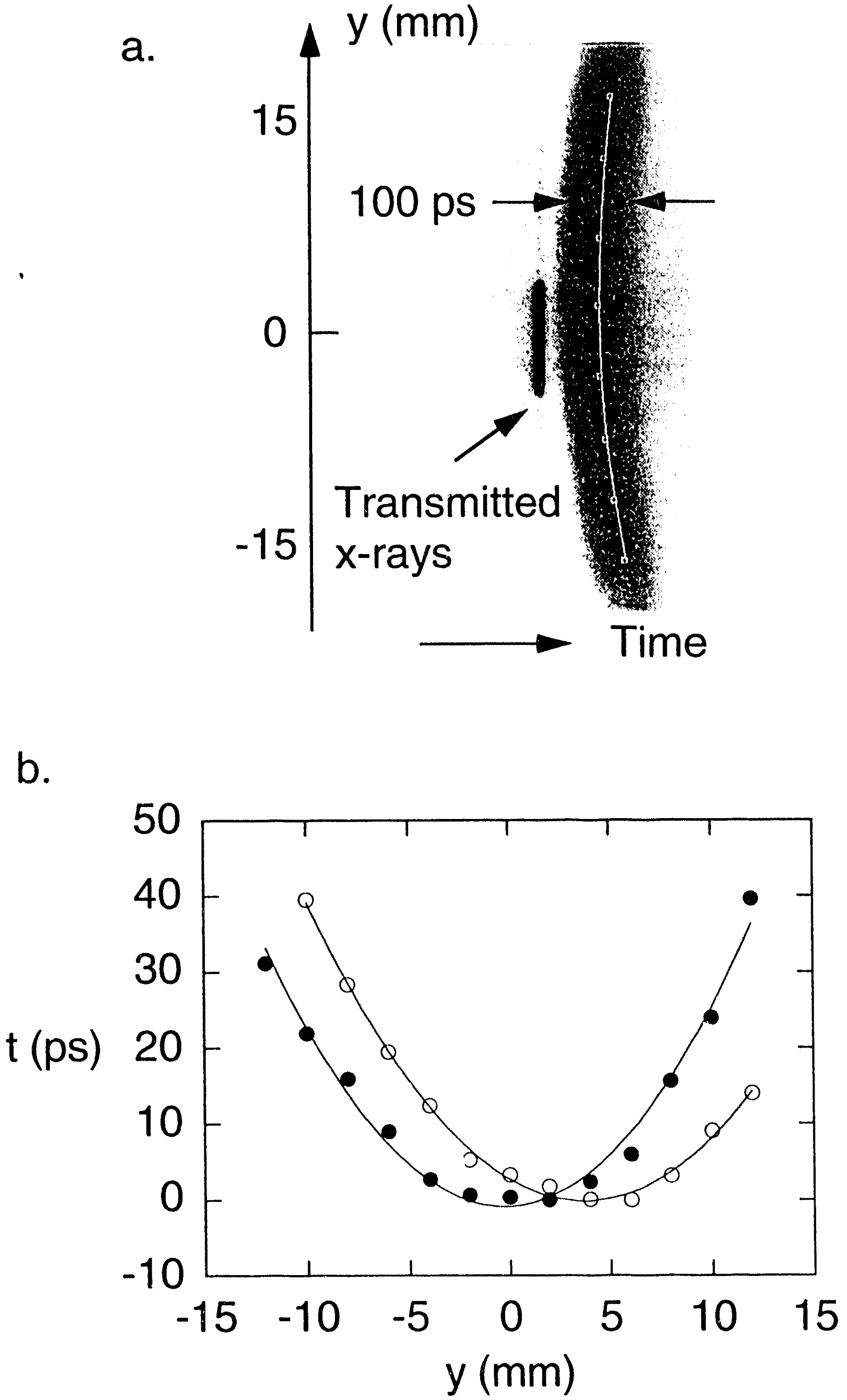
Figure 3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0
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15
y (mm)

Figure 4

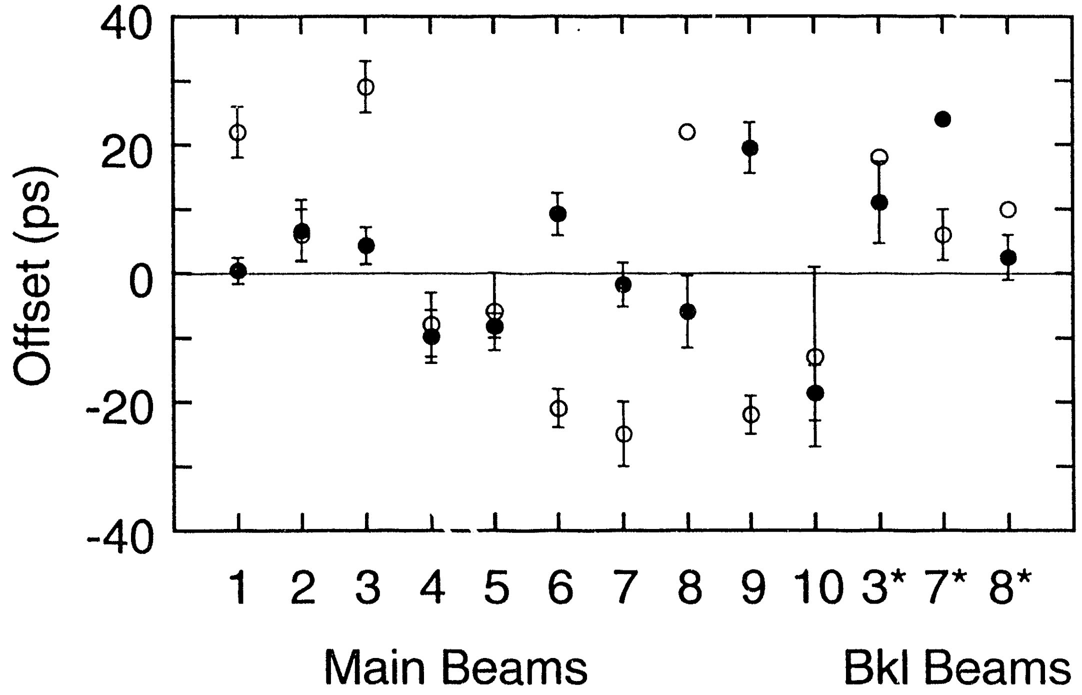

Figure 5

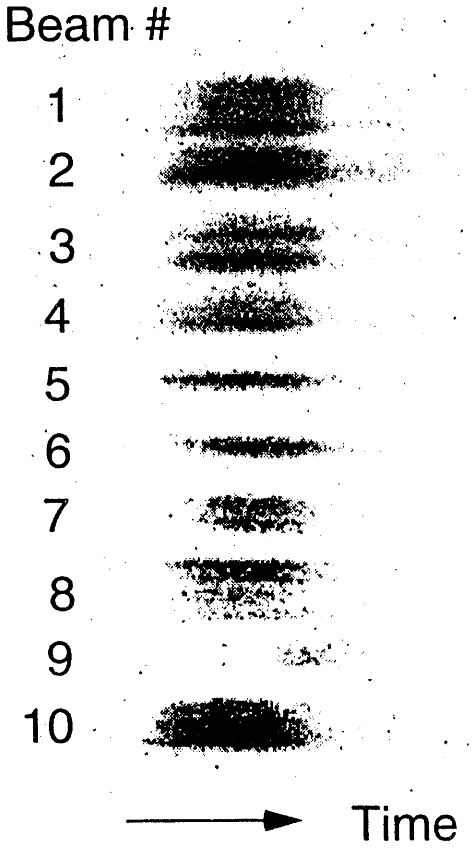

Figure 6

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